

SPECTROSCOPY OF PUTATIVE BROWN DWARFS IN TAURUS

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ABSTRACT

Quanz and coworkers have reported the discovery of the coolest known member of the Taurus star-forming complex ($L2 \pm 0.5$) and Barrado and coworkers have identified a possible protostellar binary brown dwarf in the same region. We have performed infrared spectroscopy on the former and the brighter component of the latter to verify their substellar nature. The resulting spectra do not exhibit the strong steam absorption bands that are expected for cool objects, demonstrating that they are not young brown dwarfs. The optical magnitudes and colors for these sources are also indicative of background stars rather than members of Taurus. Although the fainter component of the candidate protostellar binary lacks spectroscopy, we conclude that it is a galaxy rather than a substellar member of Taurus based on its colors and the constraints on its proper motion.

Subject headings: stars: formation — brown dwarfs — binaries: visual — stars: pre-main sequence

1. INTRODUCTION

Current surveys for brown dwarfs are exploring new regimes of temperature, mass, metallicity, age, binarity, and formation environment in order to address a variety of questions regarding objects at low masses and cold temperatures. For instance, brown dwarfs at low masses constrain the minimum mass of the initial mass function while the youngest brown dwarfs in the protostellar phase offer the most direct insight into the formation process of substellar objects.

The Taurus star-forming region ($\tau \sim 1$ Myr, $d = 140$ pc) has been the target of two recent surveys for low-mass brown dwarfs and protostellar brown dwarfs. Quanz et al. (2010) searched for the former by obtaining near-infrared (IR) images of a large sample of molecular cores in Taurus and combining these data with optical photometry from the Sloan Digital Sky Survey (SDSS; York et al. 2000; Finkbeiner et al. 2004). In the overlapping area of 1 deg^2 between the IR and optical images, Quanz et al. (2010) identified five new brown dwarf candidates and performed spectroscopy on two of them to assess their nature. Using these spectra, they classified one of the candidates, CAHA Tau 1, as a young brown dwarf with a spectral type of L2, which would make it the coolest (and likely least massive) known member of Taurus (Luhman et al. 2009).

In another survey of Taurus, Barrado et al. (2009) used archival mid-IR images from the *Spitzer Space Telescope* (Werner et al. 2004) to search for protostellar brown dwarfs. They reported the discovery of a $2''.5$ pair of candidates that could comprise a binary system, which were

designated as SSTB213 J041757.75+274105.5 A and B (henceforth J041757 A and B). Although spectroscopy was unavailable for these objects, Barrado et al. (2009) concluded that the proper motion of the A component supports its membership in Taurus and that the colors of the B component are inconsistent with a galaxy, which is the primary source of contamination in a survey for protostellar brown dwarfs.

We have performed IR spectroscopy on CAHA Tau 1 and J041757 A to determine whether they are young brown dwarfs. We also have used the available colors and proper motion measurements for these two objects and the remaining candidates from Quanz et al. (2010) and Barrado et al. (2009) to determine if they are likely to be substellar members of Taurus.

2. OBSERVATIONS

We obtained low-resolution near-IR spectra of CAHA Tau 1 and J041757 A with SpeX (Rayner et al. 2003) at the NASA Infrared Telescope Facility (IRTF). We used the prism mode of SpeX with a $0''.8$ slit, which provided a wavelength coverage of $0.8\text{--}2.5 \mu\text{m}$ and a resolution of $R \sim 150$. We collected 12 and 16 exposures of CAHA Tau 1 on the nights of 2010 January 3 and 4, respectively, and 20 exposures of J041757 A on the night of 2010 January 16. The images had exposure times of 90 s and were taken during dither sequences between two positions along the slit. The observations of CAHA Tau 1 were performed with the slit rotated to the parallactic angle. For J041757 A, we aligned the slit so that it encompassed the A and B sources simultaneously. Spectra that are not obtained at the parallactic angle are susceptible to wavelength-dependent slit losses, but such losses should be negligible for the observations of J041757 since they were performed at a very low airmass (≤ 1.03). These data were reduced with the Spextool package (Cushing et al. 2004) and corrected for telluric absorption (Vacca et al. 2003). The average signal-to-noise ratios were ~ 30 and 12 per pixel for CAHA Tau 1 and J041757 A, respectively. We smoothed the reduced spectra to a slightly lower resolution ($R \sim 135$) to improve these ratios. The resulting spectra for CAHA Tau 1 and J041757 A are presented in Figure 1. A small portion of

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the spectrum of J041757 A is not shown because it falls between the atmospheric windows where the telluric correction was very poor. The detection of J041757 B was too weak for a useful spectrum.

3. ANALYSIS

3.1. Spectral Classification

Using IR spectroscopy, Quanz et al. (2010) classified CAHA Tau 1 as a young brown dwarf with a spectral type of $L2 \pm 0.5$. If J041757 A is a member of Taurus, Barrado et al. (2009) estimated that it should have a temperature of 1550–1750 K based on a comparison of its photometry to the fluxes predicted by theoretical evolutionary models, which also corresponds to an L spectral type (Dahn et al. 2002). To assess the accuracy of these classifications, we begin by comparing our spectra of CAHA Tau 1 and J041757 A in Figure 1 to a spectrum of one of the coolest known members of Taurus, KPNO 4 (M9.5; Briceño et al. 2002), which has been reddened to roughly match the spectral slopes of the two candidates. The most prominent features in the spectrum of KPNO 4 are the deep H_2O absorption bands. CAHA Tau 1 and J041757 A should show H_2O bands that are as strong or stronger as those in KPNO 4 if they are L-type members of Taurus, but this is not the case. Instead, CAHA Tau 1 exhibits weak H_2O absorption that is indicative of a spectral type of M5–M6 if it is a dwarf and M3–M4 if it is a young star⁵. The absence of detectable H_2O absorption in the spectrum of J041757 A places constraints of $\lesssim M2$ (dwarf) and $\lesssim M0$ (young) on the spectral type. The near-IR absorption features from the photospheres of young stars can be diluted by continuum veiling from circumstellar dust emission, but this is not a possible explanation for the absence of strong H_2O absorption for CAHA Tau 1 and J041757 A since they do not exhibit IR excess emission (Section 3.2.3). Both candidates are much too faint to be members of Taurus with spectral types of M3–M4 and $\lesssim M0$. Thus, we classify them as background stars rather than substellar members of Taurus.

3.2. Photometric Classification

3.2.1. Sources of Photometry

In addition to spectroscopy, we have used the available photometry to examine whether the candidates from Quanz et al. (2010) and Barrado et al. (2009) are likely to be young brown dwarfs. We have retrieved photometry in the five optical bands of SDSS (*ugriz*; Fukugita et al. 1996) from the Sixth Data Release of the survey (Adelman-McCarthy et al. 2008) for CAHA Tau 1–5 and J041757 A (the B component was not detected by SDSS). The calibration of these images is described by Padmanabhan et al. (2008). We selected the data measured with an aperture radius of $1.745''$. Barrado et al. (2009) measured i and z photometry for J041757 A and B from archival images from the Canada-France-Hawaii Telescope (CFHT). The data for J041757 A from Barrado et al. (2009) agree with those from SDSS, which suggests that the two photometric sys-

tems are similar. Therefore, we have adopted the i and z photometry from Barrado et al. (2009) for J041757 B.

We have compiled photometry at J , H , and K_s from the Two-Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) for CAHA Tau 1, 2, 4, and 5, from Quanz et al. (2010) for CAHA Tau 3, and from Barrado et al. (2009) for J041757 A and B. All of these sources also appear within archival images at 3.6, 4.5, 5.8, 8.0, and 24 μm that were obtained by the *Spitzer Space Telescope*. We have measured photometry from these images using the methods that were applied to the known members of Taurus by Luhman et al. (2010). J041757 B becomes increasingly dominant over J041757 A at longer wavelengths, as shown in Figure 2. To measure photometry at 3.6 and 4.5 μm for J041757 A, we subtracted a scaled point spread function (PSF) at the location of J041757 B (Marengo et al. 2006). The A component was not detected in the PSF-subtracted images at 5.8 and 8.0 μm . The spatial resolution of the image at 24 μm is too low for resolving J041757 A and B. We have assigned all of the 24 μm flux to J041757 B since it is much redder than J041757 A at 3.6–8.0 μm . We have adopted the average measurement in a given band if an object was observed at multiple epochs by *Spitzer*. We did not measure photometry from the second epoch of images at 3.6 μm for J041757 A and B because they were contaminated by cosmic rays. Our measurements of *Spitzer* photometry for CAHA Tau 1–5 and J041757 A and B are presented in Table 1.

3.2.2. Optical and Near-IR Colors

To determine if the candidates from Quanz et al. (2010) and Barrado et al. (2009) have the appropriate optical colors and magnitudes for low-mass members of Taurus, we plot them on a diagram of i versus $i - z$ in Figure 3 with all known late-type members of Taurus ($> M6$) that were detected by SDSS. We include in that diagram all other point sources in the SDSS images that have photometric uncertainties less than 0.1 mag. All of the candidates appear below the sequence of known members, which indicates that they are probably field stars or galaxies. CAHA Tau 2, 4, and 5 were detected in the survey by Luhman (2004) and were identified as probable nonmembers for the same reason. One additional candidate, CAHA Tau 3, was encompassed by the images from Luhman (2004), but its signal-to-noise ratio was too low for useful photometry. Young stars that are occulted by circumstellar disks and seen in scattered light can appear anomalously faint for their colors, but J041757 B is the only candidate that shows possible evidence of a disk in its mid-IR photometry (Section 3.2.3).

A diagram of $i - K_s$ versus $J - H$ is useful for distinguishing between late-type objects and reddened stars at earlier types (Luhman 2000). We show a diagram of this kind in Figure 3 for the candidates from Quanz et al. (2010) and Barrado et al. (2009), the known late-type members of Taurus, and all other sources with errors less than 0.1 mag in the SDSS and 2MASS images of Taurus. CAHA Tau 2 is the only candidate that has the appropriate colors for a young object later than M6. Given its position in i versus $i - z$, it is probably a field M dwarf rather than a low-mass member of Taurus.

3.2.3. Mid-IR Colors

⁵ H_2O absorption is stronger in pre-main-sequence objects than in dwarfs at a given optical spectral type (Luhman & Rieke 1999; Lucas et al. 2001; McGovern et al. 2004).

Approximately half of the known brown dwarfs in Taurus exhibit red mid-IR colors that indicate the presence of circumstellar disks (Luhman et al. 2010). We can check for this signature of youth in the mid-IR photometry for the candidate brown dwarfs from Quanz et al. (2010) and Barrado et al. (2009). According to our *Spitzer* measurements in Table 1, CAHA Tau 1–5 and J041757 A have neutral colors (< 0.2) that agree with those of stellar photospheres, and thus do not show evidence of disks. The remaining candidate, J041757 B, does have a very red IR spectral energy distribution, which was the basis of its original identification as a candidate protostellar brown dwarf by Barrado et al. (2009). As demonstrated in that study, the mid-IR colors of J041757 B are similar to those of known protostars in Taurus.

Based on a comparison to extragalactic surveys with *Spitzer*, Barrado et al. (2009) concluded that a single type of galaxy could not account for all of the mid-IR colors of J041757 B. However, we find that the *Spitzer* colors of this object are fully consistent with those of active galactic nuclei (AGN, Lacy et al. 2004, 2007; Stern et al. 2005; Donley et al. 2007; Barmby et al. 2008). This is illustrated in Figure 4, where we show two *Spitzer* color-color diagrams for J041757 B and a sample of sources that have been spectroscopically classified as AGNs (Sacchi et al. 2009) from the *Spitzer* Wide-area Infrared Extragalactic Survey (SWIRE, Lonsdale et al. 2003, 2004). ELAIS15 J003603-433152 is an example of an AGN from SWIRE whose *Spitzer* colors agree closely (≤ 0.16 mag) with those of J041757 B. We also include in Figure 4 all sources detected in *Spitzer* images of Taurus that have $[3.6] > 11$, photometric errors less than 0.1 mag in all bands, and are not known members of the star-forming region (Luhman et al. 2009, 2010). This sample contains ~ 2400 objects and should be dominated by background sources, mostly AGN and other red galaxies. The mid-IR colors of J041757 B place it within this background population as well.

After examining the colors of J041757 B at optical and near-IR wavelengths, Barrado et al. (2009) found that it is redder than galaxies from extragalactic surveys like SWIRE in $I - J$ and $J - [3.6]$, leading them to conclude that it is not a galaxy. However, as shown in Figure 6 from Barrado et al. (2009), the colors of J041757 B are consistent with a galaxy reddened by $A_V \sim 5$, and the presence of extinction is naturally explained by the Taurus dark cloud against which J041757 B is projected. Indeed, the shape of the spectrum of J041757 A, which is a background star near the same line of sight, exhibits a reddening that corresponds to $A_V \gtrsim 5$. The dust map from Schlegel et al. (1998) indicates a similar extinction at this position, although its spatial resolution is low (FWHM=6'.1).

3.3. Proper Motions

Quanz et al. (2010) and Barrado et al. (2009) measured proper motions for their candidates and compared these data to proper motions of known Taurus members to assess whether they are likely to be members. In this section, we examine the proper motion analysis from each of those studies.

Quanz et al. (2010) found that the proper motions of CAHA Tau 1 and 2 agreed with those of the known members of Taurus. However, the motions of the two candi-

dates differed by only 1.3 and 1.9 σ , respectively, from a simulated population of background giants because of the large proper motion uncertainties. According to Quanz et al. (2010), the sizes of the motions of CAHA Tau 1 and 2 were also consistent with those expected for field dwarfs. Indeed, we classified CAHA Tau 1 as a M6 dwarf based on our spectroscopy in Section 3.1. Quanz et al. (2010) concluded that the uncertainties in the proper motions for the remaining candidates, CAHA Tau 3–5, were too large for useful constraints on their membership.

Barrado et al. (2009) compared their proper motion measurements for J041757 A and B to the mean and standard deviation of the motions of known Taurus members that were computed by Bertout et al. (2007). Based on this comparison, they concluded that J041757 A is a member of Taurus while the data for J041757 B are inconclusive. However, the proper motion data from Bertout et al. (2007) are inadequate for identifying likely members in this manner because they include a large number of off-cloud stars that may be unrelated to Taurus, which results in a proper motion dispersion that is erroneously large. When a more reliable census of Taurus members is considered, the mean proper motion and radial velocities of the Taurus subgroups indicate that the variation among the velocity vectors of the subgroups is rather small (± 1 – 1.5 km s $^{-1}$, Luhman et al. 2009). Therefore, to assess the statistical likelihood of membership for J041757 A and B, we compare their proper motions to the mean motion of the nearest Taurus subgroup (II): $\mu_\alpha, \mu_\delta = +6.0 \pm 1, -26.8 \pm 1$ mas/yr (Luhman et al. 2009). We assume that the absolute proper motions of J041757 A and B are the same as the relative values measured by Barrado et al. (2009): $\mu_\alpha, \mu_\delta = -1.5 \pm 4.1, -20.5 \pm 3.5$ mas/yr for A and $+2.0 \pm 4.0, -5.5 \pm 3.2$ mas/yr for B. When we account for the proper motion errors and the uncertainty in the mean motion of the Taurus II subgroup, and we assume a one-dimensional velocity dispersion of 1 km s $^{-1}$ (1.5 mas yr $^{-1}$) for bona fide subgroup members, we find that $\sim 7\%$ and $3 \times 10^{-6}\%$ of bona fide members of Taurus II would have motions more deviant than that of J041757 A and B, respectively. Thus, we conclude that the motion of J041757 A is just within $\sim 2\sigma$ of the mean motion of the subgroup, but the motion of J041757 B is clearly inconsistent with membership. Meanwhile, $\sim 20\%$ of objects with no proper motion should exhibit measurable proper motions larger than that of J041757 B. Thus, the proper motion constraint for J041757 B is statistically consistent with the zero motion expected for a galaxy.

4. CONCLUSIONS

We have used IR spectra, optical and IR colors, and proper motion measurements to examine whether CAHA Tau 1–5 (Quanz et al. 2010) and J041757 A and B (Barrado et al. 2009) are substellar members of the Taurus star-forming region. We have obtained spectra of two of these sources, CAHA Tau 1 and J041757 A. The absence of strong steam absorption in their spectra indicates that they are not young brown dwarfs. We classify CAHA Tau 1 and J041757 A as reddened background stars with spectral types of M5–M6 and \lesssim M2, respectively. All of the candidates from Quanz et al. (2010) and Barrado et al. (2009) appear below the sequence of

known members of Taurus on an optical color-magnitude diagram, indicating that they are field stars or galaxies. One of these sources, CAHA Tau 2, has $J - H$ and $I - K_s$ colors that are consistent with a late spectral type ($>M6$), but it is probably a field dwarf given its position in the optical color-magnitude diagram. Six of the candidates do not show excess emission from disks in their mid-IR colors. The remaining source, J041757 B, has a red spectral energy distribution that is consistent with both a protostar and an AGN. Barrado et al. (2009) concluded that this object is too red in $I - J$ and $J - [3.6]$ to be a galaxy, but the reddening of these colors relative to galaxies at high latitudes is easily explained by the Taurus dark cloud along its line of sight. The available proper motion measurements for CAHA Tau 1–5 do not provide strong constraints on their membership in

Taurus. We estimate a membership probability of 7% for J041757 A by comparing its proper motion to those of known Taurus members. The motion of this object is consistent with a field dwarf, which is how we classify it spectroscopically. The proper motion constraints for J041757 B are inconsistent with membership in Taurus and agree with the absence of motion expected for a galaxy. Based on these various data, we conclude that CAHA Tau 1–5 and J041757 A and B are not substellar members of Taurus.

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TABLE 1
Spitzer PHOTOMETRY FOR BROWN DWARF CANDIDATES IN TAURUS

ID	[3.6]	[4.5]	[5.8]	[8.0]	[24]
CAHA Tau 1	14.63±0.03	14.42±0.03	14.5±0.1
CAHA Tau 2	14.05±0.02	13.98±0.02	13.87±0.05
CAHA Tau 3	14.53±0.04	14.40±0.05
CAHA Tau 4	12.87±0.02	12.75±0.02	12.66±0.03	12.69±0.03	...
CAHA Tau 5	13.59±0.02	13.46±0.02	13.42±0.03	13.40±0.04	...
J041757 A	15.39±0.05	15.27±0.07	>14.5	>13.5	...
J041757 B	14.81±0.02	13.80±0.02	12.78±0.03	11.70±0.03	7.82±0.04

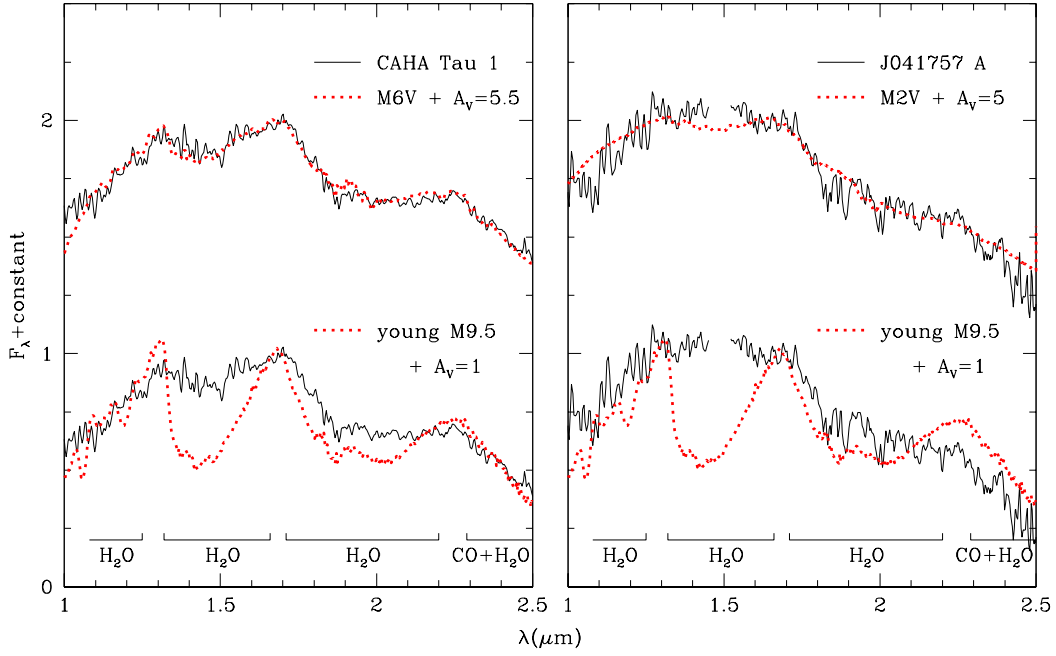


FIG. 1.— SpeX near-IR spectra of the brown dwarf candidates CAHA Tau 1 and J041757 A (solid lines) compared to data for dwarf and pre-main-sequence standards (dotted lines). These objects do not exhibit the strong steam absorption bands that are expected for young late-type objects, as illustrated in this comparison to the Taurus member KPNO 4 (M9.5; Briceño et al. 2002). Instead, CAHA Tau 1 agrees well with a reddened M6 dwarf (Gl 406) and J041757 A is earlier than \sim M2 based on its lack of steam absorption. These data have a resolution of $R \sim 135$ and are normalized at $1.68 \mu\text{m}$.

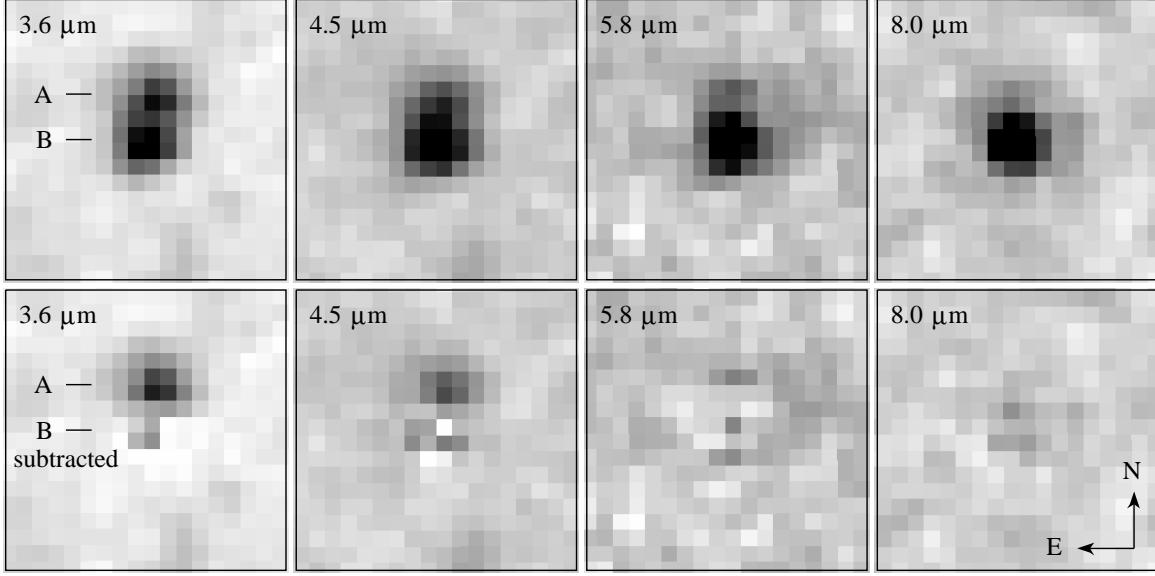


FIG. 2.— *Spitzer* images of the brown dwarf candidates J041757 A and B before and after PSF subtraction of the B component. The images have a size of $15'' \times 15''$ and are displayed on a logarithmic scale.

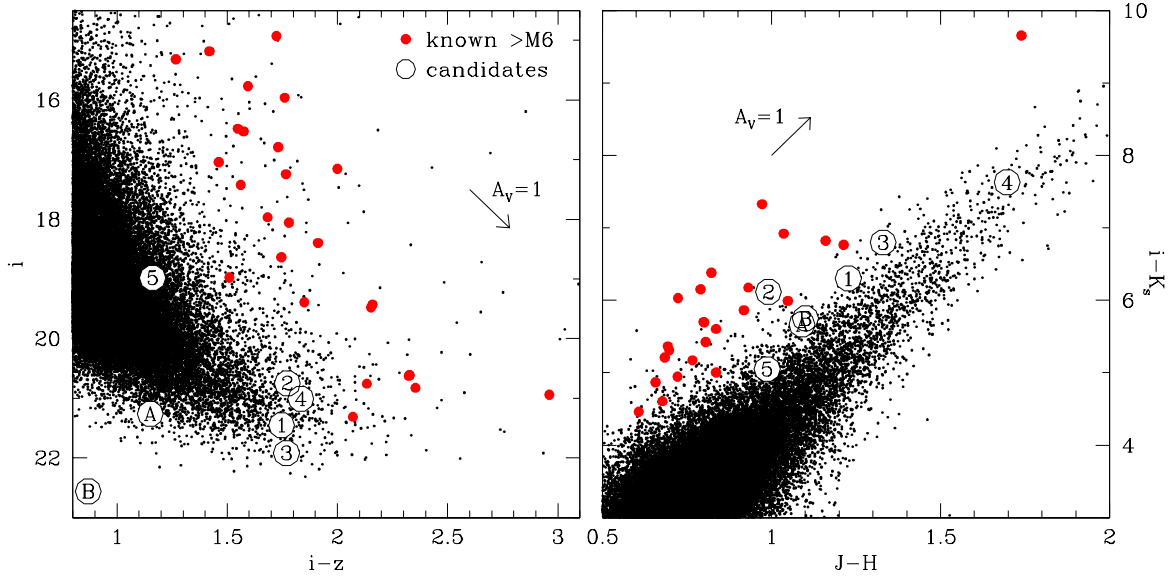


FIG. 3.— Optical and near-IR color-magnitude and color-color diagrams for the brown dwarf candidates J041757 A and B and CAHA Tau 1–5 (circles, Barrado et al. 2009; Quanz et al. 2010), known late-type members of Taurus ($>M6$, large points), and other sources detected in the SDSS survey of Taurus (small points, Finkbeiner et al. 2004). The candidates appear below the sequence of known Taurus members in i vs. $i - z$, indicating that they are probably field stars or galaxies. One of the candidates, CAHA Tau 2, has $J - H$ and $i - K_s$ colors that are consistent with a spectral type later than $M6$, but it is probably a field dwarf rather than a member of Taurus given its position in i vs. $i - z$. The i and z data are from SDSS for all sources except J041757 B, which was measured with deeper archival CFHT images by Barrado et al. (2009).

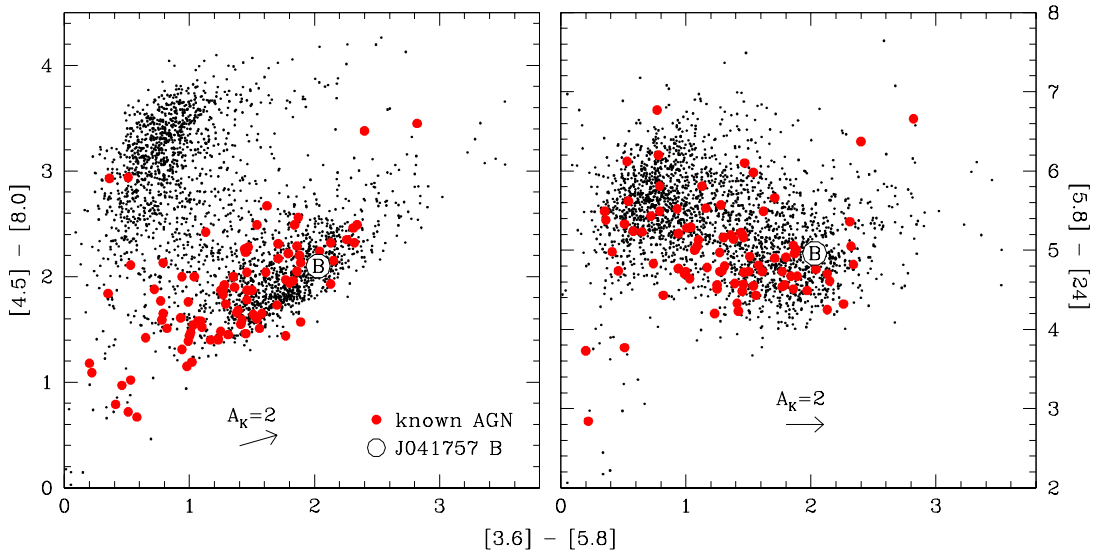


FIG. 4.— Mid-IR color-color diagrams for the brown dwarf candidate J041757 B (circle, Table 1), spectroscopically confirmed AGNs from SWIRE (large points, Sacchi et al. 2009), and faint sources ($[3.6] > 11$) detected in *Spitzer* images of Taurus (small points, Luhman et al. 2010). The colors of J041757 B are consistent with those of an AGN.